Shallow tectonics on the middle continental slope of the northeastern Gulf of Cadiz continental margin (SW Iberia)

Tectónica superficial del talud continental medio del margen continental del Golfo de Cádiz nororiental (SO de Iberia)

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Abstract: The northeastern sector of the Gulf of Cadiz continental margin has been deeply studied the last two decades. The seafloor is characterized by the Gulf of Cadiz Contourite Depositional System, strong diapirism and seepage related to the mobility of the frontal units of the Gibraltar Arc. Since 2010 high resolution bathymetric data and high and very high resolution seismic reflection and parametric echosounder profiles have improved the resolution of the previous collected data set. These data allow to analyze the middle continental slope morphology and its shallow structure with the aim to know the active tectonic processes on the seafloor. Two types of structures have been considered: (a) anticline domes and (b) normal faults which produce linear scarps and tectonic depressions. The shallow tectonics in this region is mainly related to the high mobility of geological formations in the subsoil and their ductile mechanical behaviour.

Keywords: *shallow tectonics, diapirs, normal faults, Gulf of Cadiz*

1. INTRODUCTION

The Gulf of Cadiz is characterized by the emplacement of the Gibraltar Orogenic Arc front. This tectonic arc is generated by the westward migration of the Alboran crustal domain between the upper Oligocene and the Tortonian (Maldonado *et al*., 1999). The main morphotectonic feature of the continental margin of this region corresponds to the Gulf of Cadiz Allochtonous Unit (AUGC), stationed as an accretionary wedge or mélange unit, as part of the Gibraltar Orogenic Arc (Medialdea *et al*., 2004). This tectonic unit was reactivated by extensional faults during the Messinian and the Pliocene. These faults are located close to the coast, both in the extension of the Betics Units of SW Iberia as the Rifean Units of NW Africa. The movement of these normal faults prompted the migration of this unit to the WSW in favour of the own margin gradient.

The AUGC overlaps the present-day boundary between the plates of Eurasia and Nubia. This plate border extends from the West Azores triple junction through the Gloria Fault, located westwards of the Gorringe Bank, and continues eastwards into the Gulf of Cadiz along the SWIM Fault Zone as suggested by recent models (Zitellini *et al*., 2009). This fault zone connects with the Rift-Tell System on the southern boundary of the Gibraltar Orogenic Arc (Terrinha *et al*., 2009; Rosas *et al*., 2012) (Fig. 1).

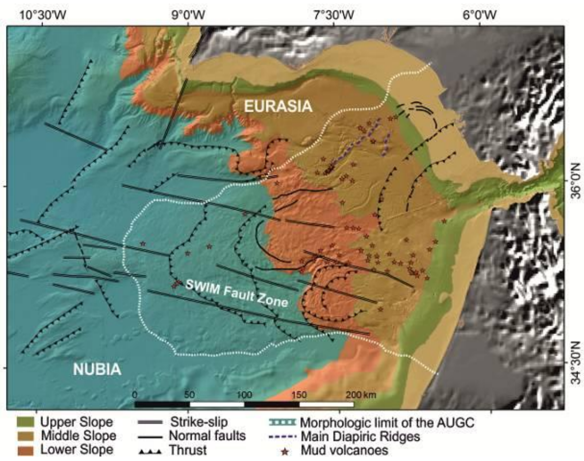

Fig. 1. Tectonic map of the Gulf of Cadiz region. Modified from Medialdea et al. (2004) and Zitellini et al. (2009).

The different geodynamic models appoint to a NW-SE oblique convergence of 2 to 5 mm/yr between the plates of Eurasia and Nubia (Nocquet, 2012 and references therein). Geodetic data from continuously recording GPS stations (CGPS) and survey-mode GPS sites show a roughly NW–WNW displacement in the western part of the Betics Cordillera (Koulali *et al*., 2011 and references therein) with respect to the Iberian Massif. These data demonstrate that the structures that constitute the Gibraltar Arc continue actives at present.

The main aim of this contribution is to analyze the shallower tectonic structures that affect the sedimentary units at the middle slope of the northeastern Gulf of Cadiz continental margin.

2. MATERIAL AND METHODS

A wide data set of seismic reflection profiles and multibeam bathymetry (EM 12-120 and TOPAS PS18) has been obtained since 1996 in the northeastern area of the Gulf of Cadiz continental margin during TASYO and MVSEIS projects. In the last four years high resolution bathymetric data (EM 3002D, EM710, EM300, EM302) and high and very high resolution seismic reflection and parametric echosounder profiles (TOPAS PS18) have been acquired and have improved the resolution of previous data set. Recent data were acquired as part of the LIFE+ INDEMARES-CHICA (CHICA0610, CHICA1011, CHICA0412), CADHYS (CADHYS0713) and ARSA (ARSA0313) projects on board the R/V Emma Bardan, R/V Vizconde de Eza, R/V Miguel Oliver (from MAGRAMA) and R/V Ramon Margalef (IEO) (Fig. 2). Bathymetric data were processed with Caris Hips & Sips software to create bathymetric models at 15 m resolution. Seismic and parametric profiles have been imported to Kingdom IHS software for geological interpretation in SEG-Y format. Morphologycal analyses were performed using an ArcGIS desktop software.

3. SEAFLOOR CONTROLS

Continental margin structure is strongly conditioned by the Upper Oligocene-Tortonian tectonic and gravitational emplacement of the Gibraltar Arc orogenic front to form the AUGC. The structure of this unit is characterized by thrust faulting affecting both their frontal and lateral ramps, meanwhile at the northeastern part several normal listric faults affecting Upper Miocene, Pliocene and Quaternary units have been developed and rooted into this unit (Fig. 1). Its internal configuration is very chaotic and strongly deformed, defined as a tectonic mélange. The AUGC is characterized by sedimentary formations of low density, consisting of Triassic evaporates and Upper Cretaceous to Miocene marls and shales with older blocks (Maldonado *et al*., 1999). The northeastern sector of the Gulf of Cadiz has a significant thickness, reaching 2 to 2.5 km. Although its base is not well controlled in seismic reflection profiles (Medialdea *et al*., 2004). The low density geological formations are the source of diapiric structures of high complexity.

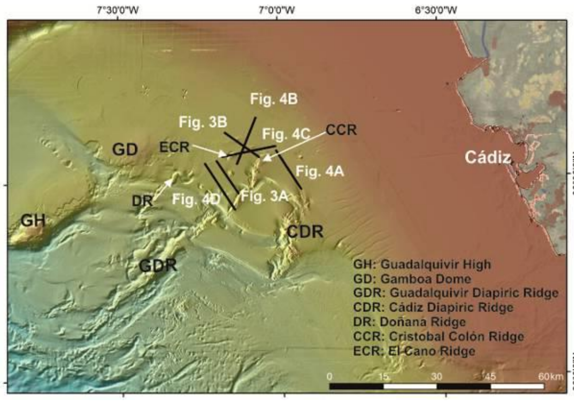

Fig. 2. Bathymetric map of the northeastern Gulf of Cadiz continental margin. Location of seismic profiles.

Seafloor features are primarily controlled by three main processes. First, the diapirism developed in this region that control a series of elongated ridges on the seafloor with a roughly sub-parallel trend according to the longitudinal direction of the AUGC (Fernandez-Puga *et al*., 2007). Secondly, the Mediterranean Outflow Water (MOW) bottom dynamics produces the occurrence of the Depositional Contourite System of the Gulf of Cadiz. This interaction generates a set of erosive (contourite channels, moats, furrows) and depositional (mounded, sheeted, plastered drifts) morphological types (Hernandez-Molina *et al*., 2014 and references therein). Besides, the interplay between diapiric structures and water masses dynamics produces a number of secondary features such as blinded valleys, marginal channels, landslides and erosive circular depressions (García *et al*., 2009; Leon *et al.,* 2010).

Lastly, seepages processes related to this fluid mobility in the subsurface (mainly brines and hydrocarbons) often follow the pattern of tectonic structures, as pathways for fluids migration underneath seafloor surface. The results of these extrusions are mud volcanoes (Fig. 1) or pockmark like features on seafloor (Medialdea *et al.,* 2009).

4. SHALLOW STRUCTURAL TYPES

In spite of the complex structure and great tectonic activity in this region of the continental margin, there are not many tectonic structures affecting the seafloor and the upper Pleistocene-Holocene sedimentary units.

Basically, the main structures observed in the seafloor correspond to the diapiric elevations. These structures produce two large-length ridges (Cádiz Ridge – 40 km and Guadalquivir Ridge – 86 km) and several minor ones (including Doñana Ridge, Cristobal Colón Ridge and El Cano Ridge – between 2 and 5 km length), all of them with a general NE-SW orientation.

These ridges and their associated diapirs have been linked in depth to transpressional transfers of extensional fault systems located in the northeastern part of the margin, or even directly to reverse faults according to the present-day tectonic kinematics (Fernández-Puga *et al.*, 2007).

Regardless of the seafloor features related to the main diapirs, the Gulf of Cadiz Contourite Depositional System and seepage, two types of structural reliefs are observed in this sector of the continental margin:

i) Smooth dome anticline folds (Fig. 3). They are slightly elongated following NE-SW to E-W orientations, their lengths vary between 1 and 5 km, reaching a maximum of 15 km in the Dome of Gamboa and reliefs between 30 and 140 m respect to the adjacent seafloor.

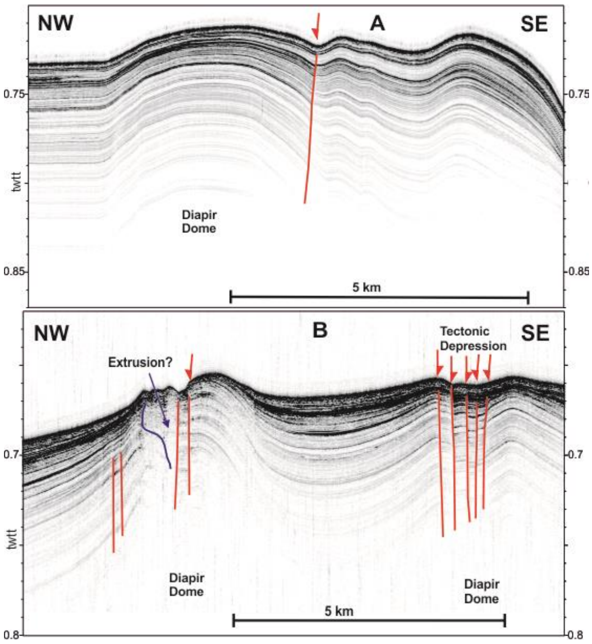

Fig. 3. Anticline domes related to buried diapirs. (A) Lateral and (B) Axial normal faults development. Location in Figure 2.

ii) Two main families of normal fault can be observed following two different trends NE-SW to E-W and NNW-SSE to WNW-ESE. In both cases, individual faults are 3-5 km long, and have vertical offsets values of 3-12 m. They are single or synthetic pair faults which produce longitudinal scarps (Fig. 4A), besides they could be associated in a graben array to form tectonic depressions, around 5 km long and 0.5 km width (Figs. 4B and 4C).

NE-SW to E-W faults are located either bounded the anticline domes (Fig. 3B) or crossing their axial part (Figs. 3B and 4B). In these cases, they may partially obliterate the overall anticline geometry of the dome on seafloor. A main lineament of 36 km long could be draw from the distribution of individual normal faults.

It is located northwards of the Guadalquivir Ridge and follows an ENE-WSW trend. NNW-SSE to WNW-ESE faults are located close to the contourite channels (Fig. 4D), but they are often related to buried diapirs without influence on the seafloor.

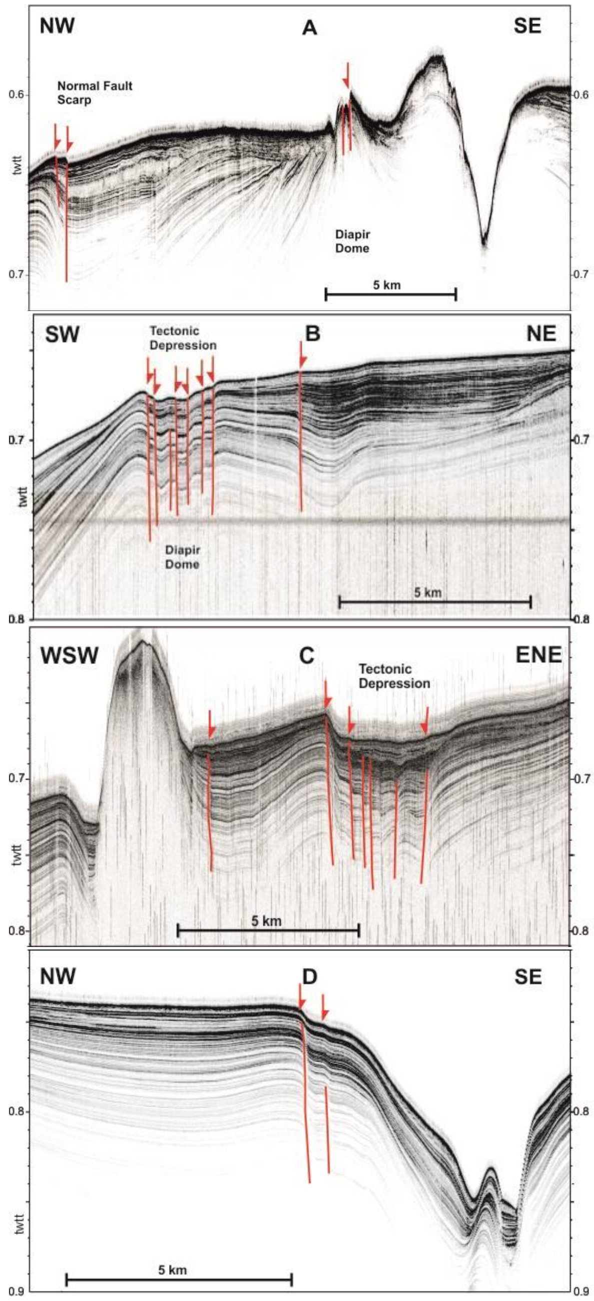

Fig. 4. Linear normal fault scarps and normal faulted depressions affecting the seafloor. Location in Figure 2.

5. DISCUSSION AND CONCLUSIONS

The presence of the AUGC in the northeastern continental margin of the Gulf of Cadiz accommodates most of the tectonic stress by ductile deformation in the shallower levels, as is indicated by the lack of earthquakes on this allochthonous complex (Bezzeghoud *et al.*, 2014). It also obliterates the deformation of the underlying structures affecting the AUGC substrate towards the seafloor. The structures that deform the seafloor and Upper Pleistocene-Holocene units are mainly diapirs with different lateral extension and elevation level. When diapirs reach the seafloor form the elongated diapiric ridges described in the literature. These ridges correspond to the outcrop of the diapir cap rock or even to the irruption into the seafloor of these structures themselves.

However, diapirs do not always uplift on the seafloor due that the elevation level is inhomogeneous. In these cases, they usually produce smooth anticlines domes affecting the seafloor and normal faults that disrupt these structures. An origin closely related to the diapir evolution must be invoked to explain the NE-SW to E-W faults, whilst a gravitational origin related to channel flank instabilities could be proposed initially for NNW-SSE to WNW-ESE faults. However, a relation between this second family of faults and diapirs in depth is often observed. This fact also appoints to a diapiric origin for these faults and even to a diapiric control for the location of contourite channels even where there are not diapirs affecting the seafloor.

In addition, the high lateral and vertical mobility of geological formations that constitute the AUGC, their ductile mechanical behaviour and the regional gradient, favour the development of extensional faults in sedimentary units overlapping buried diapirs. The important diapiric activity at different levels, ridges and domes on the seafloor produced by Upper Pleistocene-Holocene uplifting diapirs, and even diapirs without present-day influence on the seafloor controls the bottom current interaction of MOW and, in consequence, the distribution of depositional and erosive features of the Gulf of Cadiz Contourite Depositional System in this sector of the margin.

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